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ABSTRACT
Currently widespread in new urban projects, green roofs have shown a positive impact on urban runoff at the building scale, that is, decreased and slow peak discharge and decreases runoff volume. The aim was to study the possible impact of green roof at the catchment scale, more compatible with stormwater management issues. For this purpose, a distributed rainfall-runoff model (Multi-Hydro) devoted to urban environment and able to simulate the hydrological behaviour of green roof has been used to assess the green roof impact at such a scale.

It has been applied on an urban catchment (Loup basin located in the Seine-Saint-Denis county, East of Paris, France) where most of the building roofs are flat and assumed to easily accept the implementation of green roof. Catchment responses to several rainfall events covering a wide range of meteorological situation have been simulated. The simulation results show that green roof can significantly reduce runoff volume and the magnitude of peak discharge (up to 80%) depending on the rainfall event and the initial saturation of the substrate.

KEYWORDS
Green roof, source control, hydrological modelling, multi-hydro

INTRODUCTION
Green roofs have become relatively commonplace over the last 20 years in urban areas for various reasons. They may contribute to enhance the aesthetic value of buildings, but also to reduce heat island through increasing evapotranspiration, to improve the quality of the air, to protect biodiversity and to manage urban runoff. Their use in urban runoff management is surely the most significant argument used to promote their implementation because the best known and studied (Berndtsson, 2010). Indeed, at the building scale, the main performance of

green roofs in quantitative management of storm water is known to be: (i) the reduction of runoff volume at the annual scale, and (ii) the peak attenuation and delay at the rainfall event depending on the green roof structure, the rainfall intensity and the antecedent soil moisture conditions.

As roof areas represent a significant part of the surfaces of city centres (between 40 and 50%, Villarreal and Bengtsson, 2005) where no space is available for new infrastructures, green roof can also appear as a useful tool to solve operational issue at the basin scale by reducing the runoff volume and/or attenuating peak discharge. Despite the current spread of green roofs, few works have been published on their impacts on stormwater runoff to solve urban management issues. Most of the previous studies have been focused on the hydrological impact of green roof at the building scale where these impacts initially occur: Bengtsson, 2005; Palla et al., 2008a; Palla et al., 2009; Voyde et al., 2010; Gregoire and Clausen, 2011; Stovin et al., 2012. These works usually present the results provided by an experimental green roof instrumented to collect continuous runoff and precipitation data over short periods of time (not exceeding 3 years).

To our knowledge, very few studies have been conducted at the basin scale (Carter and Jackson, 2007; Palla *et al*., 2008; Versini *et al*., 2014) and even less by using a distributed rainfall-runoff model able to take into account the spatial distribution of green roof. It is the originality of this paper, which is focussed on the hydrological impact of green roof at the basin scale.

MODEL DESCRIPTION

In order to simulate the hydrological response of the basin to rainfall events, the Multi-Hydro (Giangola-Murzyn et al., 2012) distributed rainfall-runoff model has been used. Developed at the Ecole des Ponts (open access from http://leesu.univ-paris-est.fr/-Axe-transversal-multi-hydro), Multi-Hydro is a numerical platform that makes interact several models, each of them representing a specific portion of the water cycle in an urban environment: surface runoff and infiltration depending on a land use classification (roads, houses, gullies, green spaces, water bodies are differentiated), sub-surface processes and sewer network drainage (representing the layout of conduits and nodes).

A specific module dedicated to simulate green roof behaviour has been added in Multi-Hydro. It is inspired from a model presented in details in Versini *et al.* (2014). Integrated among “resilience infrastructure” Multi-Hydro options (already comprising basin and barrier), this module is applied on each cell previously identified as green roof during the land use analysis. Using a reservoir model structure, it produces for each time step a modified rainfall field representing the green roof response for green roof cells and conserving the original rainfall for the remaining cells. These new rainfall fields are then used as input data for the complete Multi-Hydro cycle. Within these loops, green roof cells are considered as standard roof; i.e. impervious pixels whose water is directly routed to the nearest gully.

Based on green roof properties (thickness, porosity, field capacity, hydraulic conductivity), this module is theoretically able to represent a wide range of green roof configurations. To ensure its validity, the Multi-Hydro green roof module was tested to represent the hydrological response of a monitored experimental green roof located in Trappes (20 km from Paris, France) and supported by the CETE Ile-de-France. This green roof comprises an extensive vegetation layer (sedum), a growing medium layer (thickness of 3 cm) and a drainage layer with expanded polystyrene. The module was successfully validated for the five main rainfall events that occurred during the monitoring period. Several values of initial saturation of the substrate (ranging 10 to 90%) were tried to represent as well as possible the hydrological response of the green roof. Table 1 synthesized the results. Simulations and observations matched very well (Nash criterion is always higher than 0.8). It also appears that the substrate is relatively saturated in winter, whereas it is dryer in summer. At the beginning of the last event, the substrate is saturated about 40% because it rained 40 mm during the previous week.

Table 1. Validation of the Multi-Hydro green roof module for the 4 main rainfall events of the monitoring period.

	Rainfall (mm)	Rainfall duration (h)	Nash	Initial saturation (%)
03/11/2011	21.5	5.50	0.86	50
04/12/2011	8	1.66	0.82	50
07/06/2012	9	2.00	0.90	20
18/06/2012	20	2.00	0.91	10
21/06/2012	8	0.50	0.91	40

CASE STUDY

A 65 ha test-basin, called Loup, has been selected in a highly populated and urbanized city (Villepinte, France) located close to Paris. Figure 1 displays its representation with pixels of size 10 m x 10 m inputted into the Multi-Hydro model. Only one land use type is affected to each pixel. Regarding land cover data, the basin is covered by more than 38% of building. The remaining surface is essentially covered by roads and parking lots (named as “other” in Fig 1), making the basin highly impervious (close to 90%). Most of the buildings are dedicated to industrial activities. The corresponding industrial building roof area represents more than 34% of the basin area (16.7 ha). For the rest of the study, it has been assumed that these building roofs are flat and that the implementation of green roof is technically possible.

The outlet of the basin is drained into a storage basin whose water level is monitored in real time. At the beginning of a rainfall event, the storage basin outlet gate is closed to limit flows in the downstream sewage network. Hence, the volume stored in the basin, which can be related to the water height, corresponds to the discharge generated by the basin at the outlet. Using this data on four rainfall events, Multi-Hydro implemented with a 10 m resolution was previously validated on the Loup basin (see Gires et al., 2013; Abbes, 2013). The same model was used here.

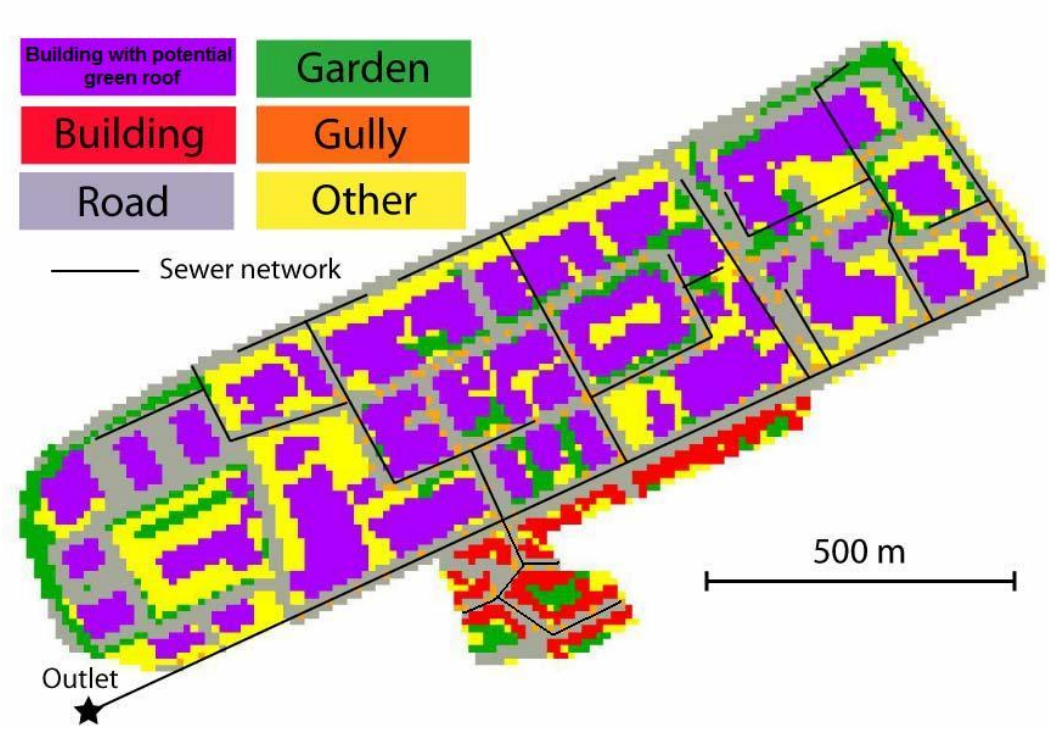

Figure 1. Loup basin: land use spatial distribution with pixel of size 10 m x 10 m, and sewer network inputted on Multi-Hydro

Rainfall data (resulting from a rain gauge located 1.7 km from the basin outlet) covering 2010-2012 was provided by the Water Direction of the Seine-Saint-Denis County. From this database, 16 rainfall events have been extracted to assess the hydrological impact of the green roof implementation in the Loup basin. These events differ by their characteristics in terms of rainfall accumulation (from 6 to 40.6 mm) and rainfall duration (from 0.5 to 8.2 hours). Corresponding return periods vary between one month to more than five years (Table 2).

Table 2. Characteristics of the rainfall events and corresponding evaluation indicators depending on the initial state of substrate saturation

				IS=50%		IS=30%		IS=10%	
Date	Rainfall (mm)	Duration (h)	Return period	*ΔV* (%)	*ΔQp* (%)	*ΔV* (%)	*ΔQp* (%)	*ΔV* (%)	*ΔQp* (%)
14/07/2010	40,60	5,17	5<<10 yrs	11,0	9,3	15,3	8,8	19,9	9,2
12/07/2010	32,60	2,40	2<<5 yrs	2,5	2,6	8,6	3,7	14,5	6,5
12/06/2010	26,40	2,33	1 year	4,6	4,7	12,3	15,7	20,1	30,1
03/06/2012	23,20	3,75	1 year	10,2	5,8	18,4	6,2	26,5	13,2
26/08/2011	23,00	4,00	1 year	1,8	-0,9	7,6	3,7	17,1	9,6
21/06/2012	15,60	0,92	1 year	3,2	2,8	15,1	10,6	34,5	29,0
05/06/2011	21,00	2,00	6 months	2,2	1,1	12,1	5,7	18,9	12,2
19/05/2012	13,20	1,40	6 months	3,5	-3,9	17,9	-2,6	35,9	6,1
03/11/2012	15,60	7,00	6 months	6,9	2,9	20,4	3,2	33,9	3,0
03/07/2010	16,00	3,15	3 months	7,5	1,2	21,3	21,1	30,1	34,5
15/12/2012	10,80	2,00	3 months	2,7	-12,1	20,0	-11,8	42,9	0,3
15/12/2011	14,40	8,17	3 months	4,8	-0,4	19,8	1,7	34,9	1,7
22/07/2011	8,80	2,00	1 month	14,1	36,7	33,2	50,3	62,4	85,9
05/08/2011	8,80	4,00	1 month	9,1	15,6	28,7	14,8	50,6	64,7
25/03/2010	6,40	5,00	1 month	26,4	8,7	57,9	38,0	77,4	81,7

23/10/2010	6,00	0,50	1 month	26,5	24,2	59,3	70,5	78,1	87,5

RESULTS AND DISCUSSION

Multi-Hydro simulations have been carried out for every rainfall event. For each event, 4 scenarios have been tested: one representing the current situation (industrial buildings are covered by impervious roofs) and three taking into account the implementation of green roof. Note that a 3 cm thickness green roof similar to that considered for validation has been used here. These three situations differ by their initial state of substrate saturation (10, 30 and 50%) considered uniform in space. As the Loup basin is very impervious (90% of its area), these initial conditions have only been modified for green roofs. Obtained results have been assessed by two indicators representing the reduction in terms of runoff volume (ΔV) and peak discharge (ΔQp):

$$\Delta Qp\ (\%) = \frac{(Qp\_imp - Qp\_gr)}{Qp\_imp} \times 100$$

$$\Delta V\ (\%) = \frac{(V\_imp - V\_gr)}{V\_imp} \times 100$$

Where *Qp_imp* and *V_imp* refer to peak discharge and runoff volume computed for the impervious situation whereas *Qp_gr* and *V_gr* correspond to those computed for the different green roofing scenarios.

It has to be noticed that results are less pronounced than those usually observed at the building scale because they depend on the green roof area, representing only 34% of the basin area. Nevertheless, green roof appears to significantly impact urban runoff in terms of peak discharge and runoff volume depending on precipitation and the initial state of the substrate saturation (see Table 2). These reductions can reach around 80% for the more favourable cases (the smallest events with a low initial saturation).

For some moderate saturation conditions (IS=30%), volume runoff reduction is almost always higher than 10% and clearly related to the return period characterizing the rainfall event. When the total amount of precipitation is lower than 20 mm, the implementation of green roof provides the retention of at least 20% of the runoff volume. In comparison, peak discharge reduction appears to be less pronounced and more related to the temporal distribution of precipitation. Indeed, this reduction can be higher than 10% for a large range of situations: low and moderate rainfall accumulation or intensity. When the event is composed of several rainfall peaks (as Figure 2 top), green roof is able to store the first mm of precipitation and attenuate the corresponding first peak discharges. Nevertheless, the following peaks remain unchanged because substrate is saturated and has no time to recover its storage capacity. In very few cases, the implementation of green roof can produce higher peak discharge than the impervious situation. In such situations characterized by a two rainfall peaks event, the fast response of the saturated substrate generated by the "second peak" of the rainfall coincides with the slow response of the green roof produced by the initial portion of the rainfall event.

Antecedent soil moisture condition appears as a key-factor conducting the hydrological response of green roof. More saturated is the substrate; less significant is the impact of green roof. In dry condition, the reduction in runoff volume is at least of 15% and reaches more than 30% for every current event characterized by a return period lower than one year. The reduction in peak discharge is more variable but can be higher than 60% for the more current events (see Figure 2 bottom). When substrate is saturated (IS=50%), the impact of green roof is quite limited (both reductions are lower than 10%). Only monthly events can be significantly attenuated (decrease of runoff volume and/or peak discharge higher than 10%).

The difference between a 10% and a 50% initial saturation represents a storage capacity of about 6 mm for this 3 cm thickness substrate. It seems enough to significantly reduce the consequences of a wide range of rainfall events. For this reason, the implementation of green roof is more efficient for standard and short rainfall events than for long extreme events for which the substrate could be rapidly saturated. In consequences, green roof should be more adapted to reduce the impacts of summer rainfall event than winter ones. Moreover, as evapotranspiration is higher in summer, the probability to have low initial state of the saturation substrate should be higher.

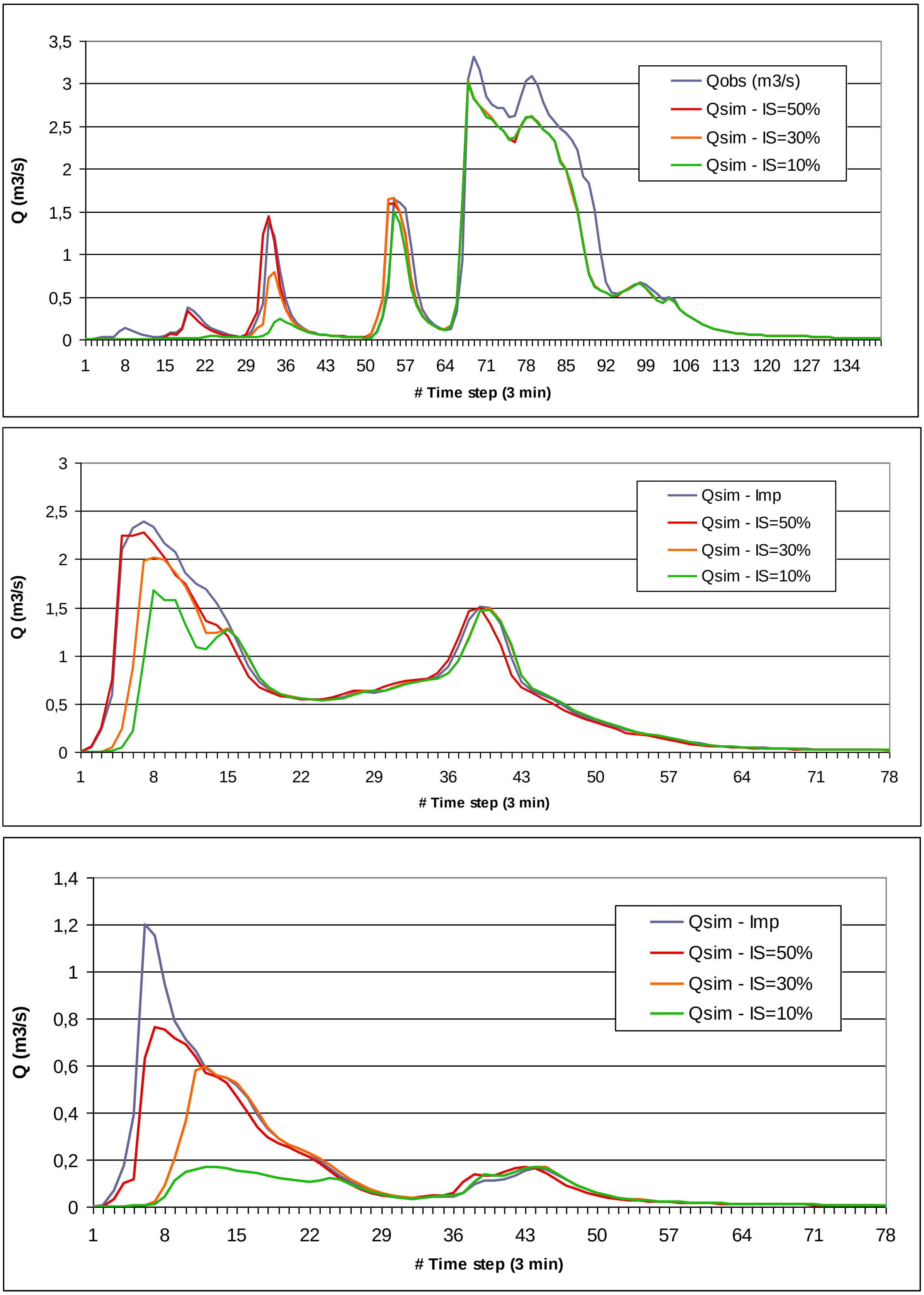

Figure 2. Simulation results obtained for 14/07/2010 (top), 12/06/2010 (middle) and 22/07/2011 (bottom) events: Qsim-Imp corresponds to the current situation (without any green roof) and Qsim-IS=50%, Qsim-IS=30% and Qsim-IS=10% to green roof situations characterized by an initial saturation of the substrate of about 10, 30 and 50%.

CONCLUSION

A distributed rainfall-runoff model especially devoted to urban environment has been improved to simulate the hydrological behaviour of green roof. It has been applied on a small urban catchment close to Paris, where 34% of the area could theoretically be covered by green roof. By simulating the catchment response to several rainfall events covering a wide range of meteorological situation, impacts on stormwater have been assessed. Green roof implementation appears to significantly reduce urban runoff in terms of peak discharge and volume depending on the temporal distribution of precipitation and the initial state of the substrate saturation. This reduction can reach more than 80% in dry condition for monthly events. It could be enough to avoid some sewage overflows situations occurring at this frequency in the Paris area.

For now the development of the Multi-Hydro platform is still in progress. Its distributed structure enables to analyse the impact of the spatial variability of the land use, and especially the precise location of green roof. It can also been used to take into account the spatial distribution of rainfall and assess its impact on stormwater management. The implementation of a more physical model to represent green roof behaviour also represents an interesting track development. It will allow testing the impact of different green roof configuration differentiating by their substrate porosity and thickness, plant species, drainage system…

Such results could appear optimistic because it has been assumed that green roofs are widely implemented. Nevertheless, the implementation of green roof could be useful to avoid some flooding issues in several cases depending on the initial conditions. Combined with other stormwater source controls, green roof could participate to significantly reduce the quantity of water flowing into the sewage network during storm events. For this reason, this work represents a good opportunity to promote the dissemination of green roof - such as other blue and green infrastructures (like bioretention swale, ponds, rain garden…) - in new urban developments and for retrofitting in already existing urban areas. In addition to thermal and environmental benefits, these infrastructures can be valuable from an urban water management point of view.

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